KICEM Journal of Construction Engineering and Project Management
Online ISSN 2233-9582

www.jcepm.org
http://dx.doi.org/10.6106/JCEPM.2015.5.2.044

Analytic Hierarchical Procedure and Economic Analysis of Pneumatic Pavement Crack Preparation Devices

JeeWoong Park[1], Yong K. Cho, Ph.D.[2], and Chao Wang, Ph.D.[3]

Abstract: Various approaches have been used in crack preparations and each of the approaches has advantages and disadvantages. Although the routing method has been widely used and seems to be the best approach among the approaches, it is not a complete solution for crack preparation. This paper compares and evaluates a pneumatic crack cleaning device (CCD) developed by Robotics and Intelligent Construction Automation group at Georgia Tech, over existing devices. Surveys were conducted to discover factors that affect the performance of crack/joint preparation work. Then, data for such information were collected via field tests for devices such as router, heat lancer, air blower and CCD. Performed field test results and follow-up interviews demonstrated that the utilization of CCD has potential to offer improvements in productivity, safety, and maintenance cost. An analytic hierarchical procedure (AHP) and economic analyses were conducted. The AHP analysis considered three factors including safety, quality and productivity while the economic analyses examined the alternatives in various ways. The results indicated that the CCD was ranked first and second for the AHP analysis and economic analysis, respectively. In conclusion, the field tests and results revealed that the utilization of CCD achieved satisfactorily in performance, quality, safety and control, and showed that it has high potential in crack cleaning practice.

Keywords: AHP, analytic hierarchical procedure, crack cleaning, pavement repair, pavement preparation, router

I. INTRODUCTION

Cracks in pavement occur when stress builds up, and is relieved, in surface layers. Various crack sealing and filling methods can be used to repair pavement surfaces, depending on crack sizes and types. In “Materials and procedures for sealing and filling cracks in asphalt surfaced pavement” (FHWA-RD-99-147), the Federal Highway Administration (FHWA) recommends crack sealing for small cracks measuring 5 to 19 mm (11). Unified Facilities Criteria (UFC) provides guidelines for crack preparation based on crack size as follows (1).

- For cracks less than 6mm, no preparation is required
- For small cracks between 6 to 19mm, rout to widen cracks to nominal width of 3mm greater than existing nominal or average width
- For medium cracks between 19 to 50mm, Sandblast, heat lance or wire brushes, followed by compressed air
- For large cracks greater than 50mm, cut and filled, prepared in the same manner as potholes

Note that UFC’s guideline and the FHWA recommendation are not identical but comparable. Problems with the traditional cracks preparing procedures were discussed in (2, 3). Merits and drawbacks of the methods are summarized.

Merits

- Air Blasting: Effectively expels dust and relatively loose contaminants; convenient and fast
- Sandblasting: efficiently removes de-icing chemicals
- Heat Lance: instantly removes moisture, warm the sealing surface, especially in cold weather; easy to follow meandering crack
- Routing: Opens small cracks or joints and cleans out debris; effective on straight cracks
- Wire Brushing: Effectively removes de-icing chemicals and vegetation on medium cracks

Drawbacks

- Air Blasting: Difficult to clean out vegetation, de-icing chemicals, large debris; unable to widen small cracks
- Sandblasting: Over-blasting can damage pavement; environmental and health concerns
- Heat Lance: Sealant bond failure (premature) caused by overheating; overheating introduces more moisture from frozen ground; high propane price; safety issues, soot residues (direct flame); unable to widen small cracks;

---

[1] Ph.D. Student, Georgia Institute of Technology, 790 Atlantic Dr., Atlanta, GA, 30332, U.S.A., jpark463@gatech.edu

[2] Associate Professor, Georgia Institute of Technology, 790 Atlantic Dr., Atlanta, GA, 30332, U.S.A., yong.cho@ce.gatech.edu (*Corresponding Author)

[3] Assistant Professor, Louisiana State University, 201 Old Forestry Building, Baton Rouge, LA 70803, U.S.A., chaowang@lsu.edu

remaining de-icing chemicals; freezing propane regulators in cold weather

- Routing: Ineffective for random narrow or wide cracks; heavy machinery may create new cracks; pulling mechanism is very dangerous in downhill; labor intensive, expensive device
- Wire Brushing: difficult to remove residual debris from narrow and small cracks

Routing only widens and excavates narrow cracks and still leaves de-icing chemicals on both sides of the crack top surface. However, surface preparation is critical for strong bonding between surface and sealing material, and thorough cleaning is essential (Figure 1). In addition, the router used by most of state DOTs for routing cracks has shortcomings, such as heavy weight, unsafe operation, slow mobility, high purchasing cost, and equipment operation/maintenance cost.

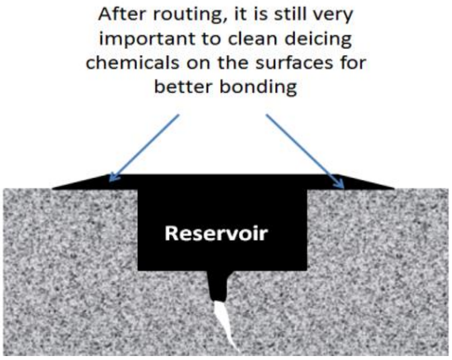


FIGURE I
ELEVATION VIEW OF ROUTED CRACK AFTER SEALING

II. MOTIVATION, OBJECTIVE AND SCOPE

Various approaches have been used in crack preparations and each of the approaches has advantages and disadvantages. Although the routing method has been widely used and seems to be the best approach among the approaches, it is not a complete solution for crack preparation. The objective of this study was to design and develop a pneumatic crack cleaning device (CCD) and compare and assess the device via field tests over other existing devices. The scope of the study includes multiple field tests and upgrades of the system.

Development of the multi-function crack cleaning device (CCD) was initiated by a request from Nebraska Department of Roads (NDOR) for a tool that efficiently prepares pavement cracks and joints for sealing. NDOR's interest extended to removing, via the tool, de-icing chemical buildup that forms in cracks and prevents sealant adhesion. The device employs a pneumatically powered rotary attachment to rout cracks and clean stubborn vegetation, old sealants, and accumulated de-icing materials from cracks.

In this research, several demonstrations and field tests were conducted on multiple versions of CCD through the support and collaboration from state and city road maintenance groups including NDOR, the City of Omaha, and Georgia Department of Transportation (GDOT). Based on the valuable, constructive feedback, the research team was able to foster the development of the CCD in multiple generations. In the following sections, the proposed system is introduced, and then field tests and discussion of the analyzed experimental results appear subsequently.

III. SYSTEM CONCEPT AND FUNCTIONS

The simple and innovative design of this tool is an air powered rotary attachment system with onboard air nozzles that simultaneously blow out cracks behind the rotary attachments. Figure 2 shows the system configuration. The CCD with the rotary motor allows for a seamless connection to existing maintenance vehicles' air compressor systems, reducing the need for retrofit costs and eliminating the need to haul flammable liquids. Although the CCD is initially developed as a multi-functional device, the NDOR was particularly interested in its routing capability. Thus, the focus of this research was placed on its routing function.

A. KEY COMPONENTS

The basic concept of the design incorporates four traditional crack/joint cleaning methods in one device: wire brushing, routing, saw cutting, and air blasting. The device uses a pneumatically driven rotary wire brush, a rotary router carbide bit to clean cracks of mid-to-large size debris and vegetation. Also, a masonry cutting blade can be attached to create a saw joint on the concrete pavement. The device was constructed with a high torque pneumatic motor, machined aluminum pipes and associated fittings, and a varied selection of the rotary attachments. The device is also equipped with an optional guide wheel, ergonomically designed shaft, and a convenient trigger mechanism. Furthermore, the device can cut a pothole area with a rotary masonry cutting blade in conjunction with a jackhammer.

B. METAL BLOCK

A metal block attached to the front of the motor provides weight to push the motor down to alleviate user fatigue and stabilize the CCD from bouncing torque. The weights of the metal block are 10 lbs for routing and 2.5 lbs for brushing and cutting.

C. WHEEL ASSEMBLY

The design of the wheel assembly was changed from one wheel to two wheels behind the motor to reduce torque-induced fatigue in the operator. This wheel configuration allows the CCD to be free-standing. The wheel assembly was initially designed foldable for easy transportation but was replaced in the 3rd generation with a

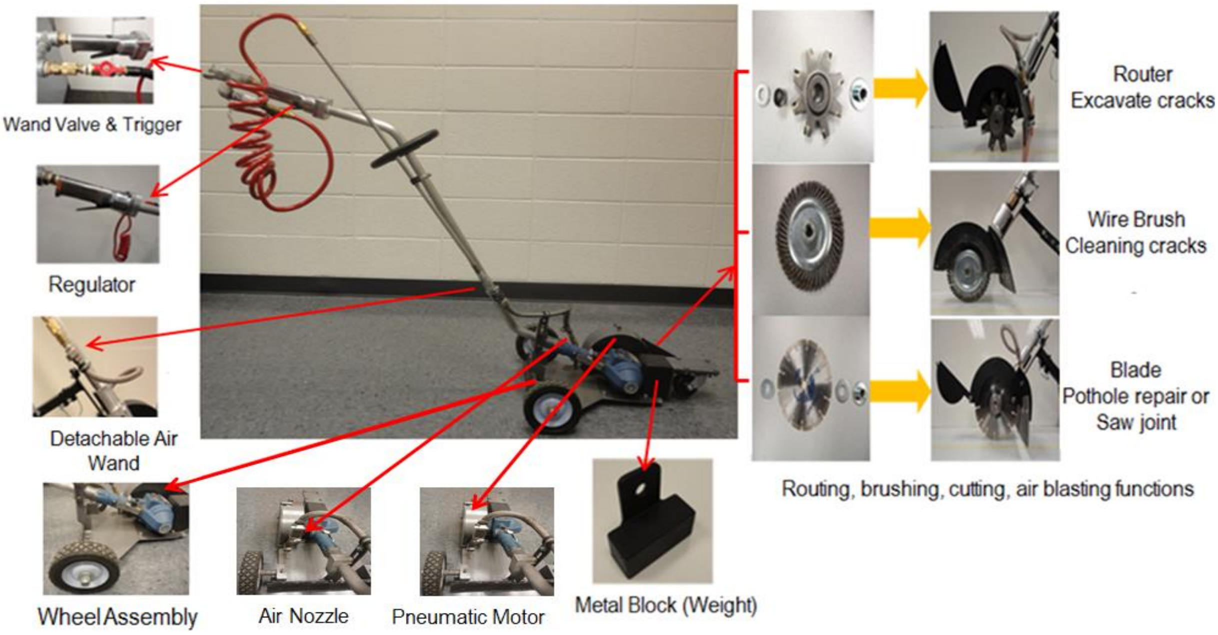


FIGURE II
VERSATILE FUNCTIONS OF CCD (3RD GENERATION)

larger and more stable frame due to its fragility during transportation. The wheels were upgraded to larger rubber foam wheels for more stability and mobility.

D. AIR WAND

Directly behind the rotary attachment, there is an air blasting nozzle to simultaneously expel fine grained particulate like concrete dust, fine sand, old sealants, and winter de-icing chemicals. Although plenty of air comes out of this nozzle to clean loose particles, a larger volume of air was still demanded to clean/chase away dirt, debris and/or vegetation. Traditionally, a leaf blower or an air wand connected to an air compressor is used by an additional laborer to clean the pavement surface. To eliminate this task, a detachable air wand (3/8” inner diameter) was designed that is easily connected to the CCD. After routing or wire brushing, the air wand can simply be detached and used by the same operator.

IV. PERFORMANCE TESTS

Eight CCD units were manufactured and delivered to each NDOR district in Nebraska. The CCD units had been used by the NDOR crews during the entire crack sealing period of 2012-2013. The performance was evaluated based on the quality of cleaned surface prior to sealing cracks.

A. TRAINING AND DEMONSTRATION AT THE NDOR

Two operation and safety training sessions and an outdoor demonstration of the CCD were conducted for NDOR crews. Three attachments (blade, router and brush) in the CCD were tested on a precast concrete block and on pavement. Also, an old sealant was removed by a router from the sealed joint on the concrete pavement.

B. ROUTING AND AIR BLASTING TESTS DURING FIELD TESTS

NDOR was particularly interested in replacing their current crack preparation methods (Figures 3, 4) with the CCD’s integrated routing and air blasting functions. Several field tests were conducted with the NDOR districts when they cleaned and sealed cracks on highways during the sealing season. While each district used the CCD for entire sealing season, the research team visited each district to measure the performance of the device and get feedback from the crews. The main purpose of the field tests was to compare routing and air blowing functions of the CCD with the current NDOR practices of air blowing, heat lancing and routing.

The routing function of the CCD was tested in conditions roughly equal to those encountered while using conventional crack cleaning methods. Comparison data between the conventional router machine and the CCD based on the NODR crew’s feedback/comments are listed in Table 1. The integration of routing/wire brushing and compressed air mechanisms allowed more efficient allocation of labor by reducing the crew size by one person. Based on the operators' statements, it is difficult to pull and control the direction of a heavy router especially against strong wind which is created by the nature or passing vehicles. When pulling the router on a downhill slope in windy conditions, the operator should pay careful attention to breaking in order to avoid overrunning. However, the CCD requires pushing motion rather than pulling motion and does not have a large surface to be potentially affected by wind, which allows ease of control over the device; thus providing safer working conditions.

FIGURE III
FIELD TESTS WITH THE NDOR ON CCD (LEFT AND MIDDLE) AND ROUTER (RIGHT)

FIGURE IV
ADDITIONAL CRACK CLEANING DEVICES: HEAT LANCER (LEFT) AND AIR BLOWER (RIGHT)

Through surveys and interviews with the NDOR crew, one of major concerns with crack cleaning was identified, which was to shorten the crack preparation time to reduce the following crack sealing group's waiting time. The conventional rotary impact router's general production rate is 12 to 15 ft/min (5). The measured average productivity of the CCD router was 26.1 ft/min (Table 2), which proves potential improvements for the productivity of the crack cleaning process. Although the average performance was enhanced, there was slight inconsistency in the production rates. Transverse and longitudinal cracks are not always straight, meaning they have different shapes of curves in different degree. In addition, different types and sizes of cracks, the slope of the roads and direction of working (uphill vs. downhill), and most importantly, the operators skills to handle all these issues are the factors influencing the productivity rates.

C. *POTHOLE REPAIR FOR THE CITY OF OMAHA*

A CCD unit was delivered to the City of Omaha road maintenance group for testing in pothole repair. The city's main interest was to test the CCD's ability to cut the asphalt pavement around a pothole area in conjunction with a jackhammer before placing a new patch. It was reported that 1.25HP CCD was enough to cut the pavement around a pothole.

TABLE I
COMPARISON DATA BETWEEN THE CONVENTIONAL ROTARY IMPACT ROUTER AND THE CCD ROUTER

	Rotary Impact Router (25 HP)	CCD Router (1.25HP) (2nd Gen)	CCD Router (4.0HP) (3rd Gen)
Equipment cost	$12,000 + maintenance cost	$1,500 (expected) + no maintenance cost	$2,500 (expected) + no maintenance cost
Average productivity	1.67 miles/day	2.25miles/day	2.4 miles/day
Crew size	7 to 8, including flag person & truck drivers	6 to 7, one person (air blowing) eliminated	6 to 7, one person (air blowing) eliminated
Strength	Heavy, ideal for straight-line cracks or concrete joint	Safe, flexible, easy to load/unload, air blowing function combined	Safe, flexible, easy to load/unload, air blowing function combined
Weakness	Heavy, expensive, difficult for downhill and windy day operations (safety concerns); may create new cracks, not convenient to move	Requires a stronger motor (e.g., 3hp or greater). Weak foldable assembly.	All reported weaknesses have been treated
Best working conditions	Longitudinal cracks, straight line concrete joint	Random cracks, longitudinal cracks, transverse cracks	Random cracks, longitudinal cracks, transverse cracks

TABLE II
CCD ROUTER PRODUCTION DATA

Test Sites		**Ave. CCD Working Speed**	**Approx. distance**	**Crack Type**	**Version of CCD**
1	Palmyra, NE	28.8 ft/min	500 ft	Transverse cracks	CCD with increased weight and larger air wand
2	Fremont, NE	22.2 ft/min	500 ft	Random cracks	CCD with increased weight and larger air wand
3	Lincoln, NE	22.0 ft/min	500 ft	Old sealant removal from concrete joints	First version of CCD
4	Gibbon, NE	22.5 ft/min	500 ft	Longitudinal cracks	First version of CCD
5	Holbrook, NE	36.6 ft/min	500 ft	Longitudinal cracks	First version of CCD
6	O’Neill, NE	24.6 ft/min	500 ft	Longitudinal cracks	First version of CCD
Average		**26.1 ft/min**	500 ft		

D. 4HP CCD Field Test (3rd Generation)

Wire brushing and saw jointing functions with the 1.25HP motor were well accepted by the NDOR crews and the city of Omaha. However, there were some concerns for the low power (1.25HP) of the CCD for routing cracks and removing old sealants. Three NDOR districts indicated that the CCD should provide more power and weight for routing cracks. To reflect the suggestions, a third generation of CCD was made mainly for routing cracks while keeping the previous 1.25HP version for multi-functional purposes (e.g., brushing and cutting).

As the third generation is mainly designed for routing cracks, it is structured with a stronger motor and more robust, stable structure while maintaining its ability to maneuver with ease and provide safety and high quality. With the help of GDOT, the new version was tested at their maintenance yard (Figure 5). The crews pointed out key benefits as follows.

1. It was equipped with an air blower and the CCD operator can easily use it without requiring an additional laborer following the routing work. This, in return, will entail an advantage of saving labor costs while allowing better allocation of labor forces.
2. High quality of crack cleaning was attained with relatively quick production rate.

The following are some other comments and observations.

3. Good stability and easy control of the CCD were achieved even on irregular cracks.
4. The performance was better than the previous version with a 1.25HP motor in terms of stability and power.

During the field tests, the productivity was measured as recorded in Table 1. A slight increased productivity rate was measured, which seemed reasonable with the motor power upgrade from 1.25HP to 4HP.

V. ANALYTIC HIERARCHICAL PROCEDURE (AHP)

Construction projects get more complex, requiring various pieces of equipment. Current technology offers various options for construction equipment, thus selecting a piece of equipment wisely and economically has a significant impact on the success of a project (8, 10). Various factors need be carefully considered and evaluated, and most importantly, the individual evaluations need be properly combined in a systematic manner. The analytic hierarchy process (AHP) is one of the well-known methods in multi-attribute decision making process.

A. Concept of AHP

AHP approach was first introduced by (12) and has been widely used in various decision-making processes. A decision is typically affected by several factors with usually different levels of importance to the decision. The more number of criteria are involved, the greater complexity follows. As the decision gets more complicated, a systematic process is desired to provide a more transparent and reliable solution to decision makers. Before analysis is implemented, basic data are collected through a survey; a typical survey format is based on the scales introduced by (13); a 1-9 scale is used to compare pairs of alternatives. Obtained numerical values are processed to relative scales of importance for criteria.

Routing on random cracks Air blowing Routed random cracks

FIGURE V.
TEST OF 4HP CCD AT A STATE DOT YARD

B. AHP Analysis for Crack Cleaning Devices

To perform an AHP analysis, criteria for the selection of crack cleaning devices were set, and a survey and interviews were conducted with field crews and superintendents at eight NDOR districts. The survey criteria were composed of three factors: safety, productivity and quality. Based on the survey results, a pairwise comparison matrix (CM) can be formulated (Equation (1)). By visual inspection of the CM in Equation (1), the elements are unfitting, that is, the scales are mathematically not matching, showing a high level of disagreement. An eigenvalue analysis provides important measures of the data, such as 3.18 and [0.9525, 0.0890, 0.2912] for λ_{max} and the weights, respectively; λ_{max} is a measure of consistency, which is used to compute a consistency ratio, and the weights represent the relative importance of the three criteria. Using λ_{max} of 3.18, a consistency ratio (CR) is calculated and compared with a consistency limit of 0.1. The computed CR is 0.176 and is greater than the limit, thus, this data set is invalid. Although the data set is unacceptable, it still provides important information regarding their ranking. It is deduced that safety is of paramount, then quality and productivity. As proposed by (6), this problematic CM can be managed by an improved AHP method to obtain the weights of the factors while satisfying the consistency check. In our analysis, however, a different approach was adopted to better account for various cases surveyed by different experts. Knowing relationships of two pairs defines a third relationship. Equation (2) describes the logic of this formulation. A CM composed by these exact scales will generate a consistency index of 0.

$$
CM = \begin{array}{c c}
\begin{array}{ccc} \text{Safety} & \text{Productivity} & \text{Quality} \end{array} & \\
\begin{pmatrix} 1 & 7 & 5 \\ \frac{1}{7} & 1 & \frac{1}{5} \\ \frac{1}{5} & 5 & 1 \end{pmatrix} & \begin{array}{l} \text{Safety} \\ \text{Productivity} \\ \text{Quality} \end{array}
\end{array} \quad (1)
$$

$$
\text{If } \frac{A}{B} = x \text{ and } \frac{A}{C} = y, \text{then } \frac{B}{C} = \frac{A/C}{A/B} = \frac{y}{x} \quad (2)
$$

Where A is one criterion, B is one of the two remaining criteria and C is the last remaining criterion.

In addition to the cases with the exact scales, the third scale (z) for each case was further scaled up and down within the consistency limit in order to cover a variety of the experts' opinions. Matrix equations (3) to (5) demonstrate how this is processed with the formulation of CM. As shown in CM2 (Equation (4)), the derived scale of A/B is 25 and it is beyond the maximum scale, 9; it means that A is 25 times more important than B. Also considering the pre-selected scale in CM2, A is 5 times more important than C. Therefore, it is reasonable to conclude that CM2 is exceedingly dominated by A, and it is seemingly not an intended case of analysis. For this reason, CM2 is discarded in further analysis. For CM1 and CM3 with their varying third scales (z), an eigenvalue analysis was performed to obtain the weights of the criteria and consistency indices. Table 3 summarizes the results for all simulations. The weights presented in the table exhibit a preference order of A (safety), C (quality), and B (productivity). For further evaluation, the performance levels with respect to these criteria for each alternative (CCD, router, air compressor, and heat lancer) have been accessed to assign a numerical evaluation. A thorough evaluation as to the three criteria was made on all the alternatives based on the performance from the field tests. Raw scores of the criteria for the alternatives are measured first and then normalized (left matrix in Equation (6)). To evaluate the alternatives for a particular case (take an example of Case 3 with y = 1.5), their weights are integrated with the corresponding scaled scores of each alternative. This evaluation is easily managed in a matrix calculation as demonstrated in Equation (6). All the cases in Table 3 were analyzed in the same manner.

$$
CM1 = \begin{array}{c c}
\begin{array}{ccc} \text{Safety} & \text{Productivity} & \text{Quality} \end{array} & \\
\begin{pmatrix} 1 & 7 & 5 \\ \frac{1}{7} & 1 & z = \frac{5}{7} \\ \frac{1}{5} & \frac{1}{z} = \frac{7}{5} & 1 \end{pmatrix} & \begin{array}{l} \text{Safety} \\ \text{Productivity} \\ \text{Quality} \end{array}
\end{array} \quad (3)
$$

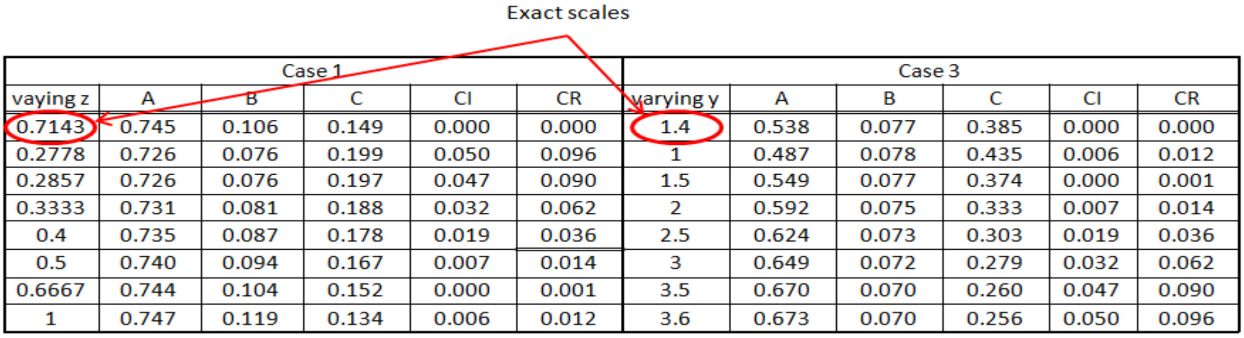
$$
CM2 = \begin{array}{c c}
\begin{array}{ccc} \text{Safety} & \text{Productivity} & \text{Quality} \end{array} & \\
\begin{pmatrix} 1 & z = 25 & 5 \\ \frac{1}{z} = \frac{1}{25} & 1 & \frac{1}{5} \\ \frac{1}{5} & 5 & 1 \end{pmatrix} & \begin{array}{l} \text{Safety} \\ \text{Productivity} \\ \text{Quality} \end{array}
\end{array} \quad (4)
$$

$$
CM3 = \begin{array}{c c}
\begin{array}{ccc} \text{Safety} & \text{Productivity} & \text{Quality} \end{array} & \\
\begin{pmatrix} 1 & 7 & z = \frac{7}{5} \\ \frac{1}{7} & 1 & \frac{1}{5} \\ \frac{1}{z} = \frac{5}{7} & 5 & 1 \end{pmatrix} & \begin{array}{l} \text{Safety} \\ \text{Productivity} \\ \text{Quality} \end{array}
\end{array} \quad (5)
$$

C. Results of AHP Analysis

Individual evaluations were aggregated and plotted in Figure 6; Case 1, Case 3 and the combined Cases 1 and 3 are plotted in the left, middle, and right, respectively. Different cases are represented by differently colored circles. Overall, it is observed that the CCD obtained the highest rank among the alternatives. The left plot (Case1) ranks the alternatives in order of CCD, air blower, heat lancer, and router. It also shows a small range of dispersion, meaning that it is relatively insensitive to the varying z values. Compared with Case1, Case3 indicates more balanced importance factors (lower safety, higher quality), yet in the same order of importance as in Case1. The rank from these plots is, on average, CCD, air blower, router, and heat lancer. This has a higher level of dispersion, meaning more sensitive to the varying y. Some instances of Case3 prove this by showing a swap of ranks

TABLE III
WEIGHTS OF THE CRITERIA AND THEIR CONSISTENCY CHECKS



Exact scales

Case 1						Case 3					
varying z	A	B	C	CI	CR	varying y	A	B	C	CI	CR
0.7143	0.745	0.106	0.149	0.000	0.000	1.4	0.538	0.077	0.385	0.000	0.000
0.2778	0.726	0.076	0.199	0.050	0.096	1	0.487	0.078	0.435	0.006	0.012
0.2857	0.726	0.076	0.197	0.047	0.090	1.5	0.549	0.077	0.374	0.000	0.001
0.3333	0.731	0.081	0.188	0.032	0.062	2	0.592	0.075	0.333	0.007	0.014
0.4	0.735	0.087	0.178	0.019	0.036	2.5	0.624	0.073	0.303	0.019	0.036
0.5	0.740	0.094	0.167	0.007	0.014	3	0.649	0.072	0.279	0.032	0.062
0.6667	0.744	0.104	0.152	0.000	0.001	3.5	0.670	0.070	0.260	0.047	0.090
1	0.747	0.119	0.134	0.006	0.012	3.6	0.673	0.070	0.256	0.050	0.096

$$\begin{array}{l|ccc|} & \text{Safety} & \text{Prod.} & \text{Qual.} \\ \text{CCD} & 0.32 & 0.23 & 0.40 \\ \text{Router} & 0.09 & 0.15 & 0.45 \\ \text{Heat Lancer} & 0.23 & 0.27 & 0.1 \\ \text{Air Blower} & 0.36 & 0.35 & 0.05 \end{array} \times \begin{array}{l|c|} & \text{Weight} \\ \text{Safety} & 0.549 \\ \text{Prod.} & 0.077 \\ \text{Qual.} & 0.374 \end{array} = \begin{array}{l|c|} & \text{Eval.} \\ \text{CCD} & 0.341 \\ \text{Router} & 0.230 \\ \text{Heat Lancer} & 0.183 \\ \text{Air Blower} & 0.245 \end{array} \qquad (6)$$

between router and heat lancer, and between router and air blower. Taken all together, the CCD proves to be the best selection. More important is that this result is insensitive to the changes in the variables, therefore, the CCD will likely be the most favorable option in any case.

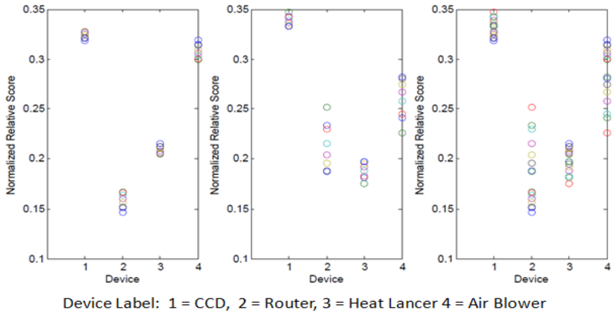


FIGURE VI.
AGGREGATED EVALUATION OF THE ALTERNATIVES; LEFT (CASE 1), MIDDLE(CASE 3), RIGHT(COMBINED

. ECONOMIC ANALYSES

Three economic analyses follow in this section to examine the economic feasibility of CCD. The analyses include annual cash flow, benefit-cost ratio and payback period analyses. For these analyses, the following assumptions and adjustments on the surveyed data are made.

1. The economic analyses only focus on quantitative monetary measures.
2. Cost data obtained from the survey are scaled, if necessary, such that the working hours per day and the working days per season are 8 and 40, respectively.
3. Labor cost and fuel costs are assumed \$15/hour/person, \$5/gallon for gasoline and \$1.5/lb for propane gas, respectively.
4. In order to avoid complication in economic analyses introduced by different alternative service lives, an annual cash flow analysis is performed. An identical replacement is assumed to be provided at the end of the equipment's service life.
5. The CCD employs a pneumatic motor, which is a relatively simpler mechanical system compared with other devices, such as a router's gasoline engine. Because of its mechanical simplicity, it is expected to have a service life at least that of a router. However, a 5 year service life was conservatively assumed.

Cost data with a list of expenses and their components for each of the devices were collected along with the performance evaluation per the experts' best knowledge and experience. The collected data indicate that some of the experts completed survey on certain devices only because of lack of enough knowledge and experience in the other devices. Scrutiny of the data reveals that they are matching relatively well without showing any outliers, allowing smooth data transition for economic analyses. As per Adjustment 2 above, the data were scaled and their averages were computed. Note that the fuel cost of an air compressor was added to each of them because the air compressor is commonly used for CCD, a heat lancer and an air blower. As an air blower accompanies with a router, the fuel of the air blower was added to the cost of the router.

Table 4 shows that a routing task requires one more crew than other devices to blow away the particles produced by the routing of cracks. An annual (seasonal) expense is calculated by summing up the average operation, maintenance and repair, fuel and labor costs. Table 4 shows an example of summarized surveyed cost information adjusted as per adjustments 2 and 3. As shown in the bottom of Table 4, the seasonal expenses, equipment cost and expected service life are extracted as the cash flow data in further economic analyses.

TABLE IV
EXAMPLE OF SUMMARIZED SURVEYED COST INFORMATION

	CCD	Router	Heat lancer	Air blower
Operation cost($/season)	400.00	1,200.00	600.00	400.00
Maintenance cost($/season)	855.00	1,074.96	10.00	10.00
Fuel cost($/season)	2,900.00	6,300.00	5,540.00	2,900.00
Crew size for crack clean	1	2	1	1
Crew size for trucks, flags, sealing, etc.	6	6	6	6
Labor cost($/season)	33,600.00	38,400.00	33,600.00	33,600.00
Sum of above	*37,755.00*	*46,974.96*	*39,750.00*	*36,910.00*
Seasonal Expenses($)	**37,755.00**	**46,974.96**	**39,750.00**	**36,910.00**
Equipment cost($)	**2,500**	**12,000**	**2,340**	**100**
Expected service life(years)	**5**	**9**	**11**	**11**

A. Equivalent Annual Cash Flow Analysis

An equivalent uniform annual cost (EUAC) was calculated based on the data in Table 4. The equipment cost for each alternative was simply converted to EUAC based on an assumed internal rate of return (IRR) (5%, 10% and 15%), then added to the seasonal expenses to obtain total EUAC. Table 5 tabulates the EUAC results. The high EUAC means the higher seasonal costs expected from using the corresponding device. The results are almost invariant with respect to the IRR. The equipment costs are insignificant compared with the seasonal expenses, therefore the effects of the initial investments are negligible. The EUAC's are in order of router, heat lancer, CCD, and air blower from high to low. In addition to the rank, the table discloses another important fact that the total EUAC of router is exceedingly higher than the others.

B. Benefit/Cost (B/C) Ratio Analysis

This section carries out a B/C ratio analysis. Additional assumption is made that state DOTs make a purchase of CCD and utilize it in their pavement cleaning work instead of the previously owned device. Benefits are estimated as the profit coming from using CCD, that is, the difference in the annual expenses of the two compared devices. Initial investment is then converted to EUAC based on assumed IRR's. For an alternative to be favorable over one another, the BC ratio needs be greater than 1, meaning the projected benefits are greater than the projected costs. Table 5 summarizes the B/C ratio results. The cases of router and heat lancer are greater than 1.0, thus the replacement with a CCD is favored in this sense. However, the case of air blower indicates with its B/C ratio less than 1, the use of CCD as an undesired replacement in a purely economic sense.

C. Payback Period Analysis

A simple payback period analysis was performed to demonstrate the length of time required to recover the cost of an investment on CCD. The annual benefit from using a CCD was deemed as the positive difference between the expenses of the previously owned device and CCD. Since using a CCD requires an initial investment of purchasing it, the cost will include a purchase of a CCD. Table 5 shows the results of the payback period analysis. It is found that the payback period is short, less than one year for a router and less than two years for a heat lancer. This attributes to the fact that the initial investment in a new CCD is relatively small while the monetary expected benefit is high. The author considers that a simple payback period analysis is sufficient without proceeding to more detailed analyses, such as a discounted payback period analysis, as the benefits are outstanding and a quick payback is expected.

TABLE V
THREE ECONOMIC ANALYSES

	IRR	CCD	Router	Heat Lancer	Air Blower
Total EUAC	5%	$38,300	$48,700	$40,000	$36,900
	10%	$38,400	$49,100	$40,100	$36,900
	15%	$38,500	$49,500	$40,200	$36,900
BC Ratio Over CCD	5%	1	16.0	3.45	-1.46
	10%	1	14.0	3.03	-1.28
	15%	1	12.4	2.68	-1.13
Payback Period Over CCD		NA	~ 0.25 years	~ 1.25 years	NA

D. Summary & Analyses of the Results

The normalized average scores of all the simulations displayed in Figure 6 are 0.331, 0.284, 0.199 and 0.186 for CCD, air blower, heat lancer, and router, respectively. Note that the AHP results are the representations of the average of all the simulations.

The results from the EUAC and BC ratio analyses show the preference of the alternatives in the same order of air blower, CCD, heat lancer, and router. Two important facts are drawn from the economic analyses besides the rank. First, the results are insensitive to the IRR. Second, the initial investments of the alternatives are much smaller than the annual expenses. It is seen from the second observation that the annual expenses are a dominating factor. The fact that varying IRR does not have any significant impact on the annual expenses, explains the first observation.

Based on the results of the two analyses, router is far worse than the other alternatives due to the following reasons. First, it needs one more laborer for air blowing, which adds an additional expense of $4,800/season. In addition, when the initial investment of a router ($12,000) is compared with those of the other alternatives ($2,500 for CCD, $2,340 for heat lancer, $100 for air blower), this difference is considerable. The additional use of an air blower adds more to operating/maintenance costs. Furthermore, a router requires more costly meticulous maintenance as it is mechanically more complex than others.

VII. CONCLUSIONS

A pneumatic crack cleaning device was designed and developed in an attempt to provide a more complete solution for crack preparation work. Crack cleaning field tests were conducted in several districts in Nebraska, NDOR, the City of Omaha and GDOT to evaluate the effectiveness of CCD and compare with the current crack cleaning device. With years of field testing, a third generation of CCD was produced based on feedback and observations. The performance evaluation collected from NDOR, City of Omaha, and GDOT, showed high potential of the CCD for improving the crack/joint preparing practice. At the close of this project, the research team concludes major findings as follows:

- It operates well on meandering cracks; its use can reduce the crew size by one person (blowing); it increases production rate; and it offers a safer alternative to conventional methods.
- Positive feedback was obtained as well with respect to maneuver, control and safety.

Not only proving its quality in performance, but a feasibility analysis was carried out to ascertain its practicality in an economic sense. Most of the districts reported saving time with the use of CCD. This serves as the most critical finding knowing that the primary concern of crack cleaning method was saving time. The AHP analysis ranked the alternatives in order of CCD, air blower, heat lancer and router while the economic analyses indicated them in order of air blower, CCD, heat lancer and router. The option of air blower itself may not generate acceptable level of quality, depending on the type of work, due to its limited cleaning capacity. Recognizing this, the CCD was the best option in all of the analyses performed herein, especially far better than the most generally used device, a router.

It is worth making a brief comparison of the proposed device (CCD) with a router. Total EUAC's for the CCD and a router are approximately $37,000 and $48,000, respectively, and the B/C analysis indicated that the replacement of a router with the CCD would deliver a high level of benefit with a B/C ratio of about 14. In addition, the payback period shows that the investment in purchasing a CCD is expected to get paid back less than a year. In summary, the various field tests and analyses revealed positive achievements in performance, quality, safety and control, and also high potential in the utilization of CCD in crack cleaning practice.

REFERENCES

[1] Basham, D.L. "Unified Facilities Criteria Asphalt Crack Repair. (UFC 3-270-02)". Department of Defense, 2001. <www.wbdg.org/ccb/DOD/UFC/ufc_3_270_02.pdf> (April 05, 2013)

[2] Haas, C., H. Chris, S. McNeil, and D. Bullock. "A field prototype of a robotic pavement crack sealing system." In Proceedings of the 9th International Symposium on Automation and Robotics in Construction(ISARC), Tokyo, Japan, pp. 313-322. 1992.

[3] Eaton, Robert A., and J. Ashcraft. "State-of-the-art survey of flexible pavement crack sealing procedures in the United States." No. CRREL-92-18. COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH, 1992.

[4] Crafco. 2008. "Installation Instruction for Mastic One." < http://www.crafco.com/PDF%20Files/Mastic/Mastic_One_AI.pdf> (May 16, 2013)

[5] Smith, K. L., and A. R. Romine. "Manual of Practice: Materials and Procedures for Sealing and Filling Cracks in Asphalt-Surfaced Pavements." Strategic Highway Research Program, National Research Council, Washington, DC, 1993.

[6] Li, Fengwei, K. K. Phoon, X. Du, and M. Zhang. "Improved AHP method and its application in risk identification.", *Journal of Construction Engineering and Management*, 139, no. 3, pp. 312-320, 2013.

[7] Park, Chan S. Contemporary engineering economics. Vol. 3. Upper Saddle River, NJ: Prentice Hall, 2002.

[8] Peurifoy, R. L., C. J. Schexnayder, and A. Shapira, Construction planning, equipment, and methods, 7th Ed., McGraw-Hill, Boston. 2006.

[9] Reynolds-Warren Equipment Co., Lake City, GA (Router Provider)

[10] Shapira, Aviad, and M. Goldenberg. "AHP-based equipment selection model for construction projects.", *Journal of Construction Engineering and Management*, 131, no. 12, pp. 1263-1273, 2005.

[11] Smith, K. L., A. R. Romine, "Materials and Procedures for Sealing and Filling Cracks in Asphalt-Surfaced Pavements". Manual of Practice (FHWA-RD-99-147). FHWA Pavement Publications. 1999.

[12] Saaty, T. L. "The analytic hierarchy process", McGraw-Hill, London. 1980.

[13] Saaty, T. L. "Decision making with the analytic hierarchy process", Int. J. Services Sciences. 2008.